GGAO – Briefing and Tour
October 4, 2006

- Briefing Agenda:

- Space Geodesy Overview	Chopo Ma	15 minutes
- SLR/SLR 2000 Programmatics	David Carter	10 minutes
- SLR 2000 Development	Tom Zagwodzki	10 minutes
- Introduction to GGAO	Jan McGarry	10 minutes
- Next Steps	Mitch/Rich	10 minutes

- Tour Agenda:

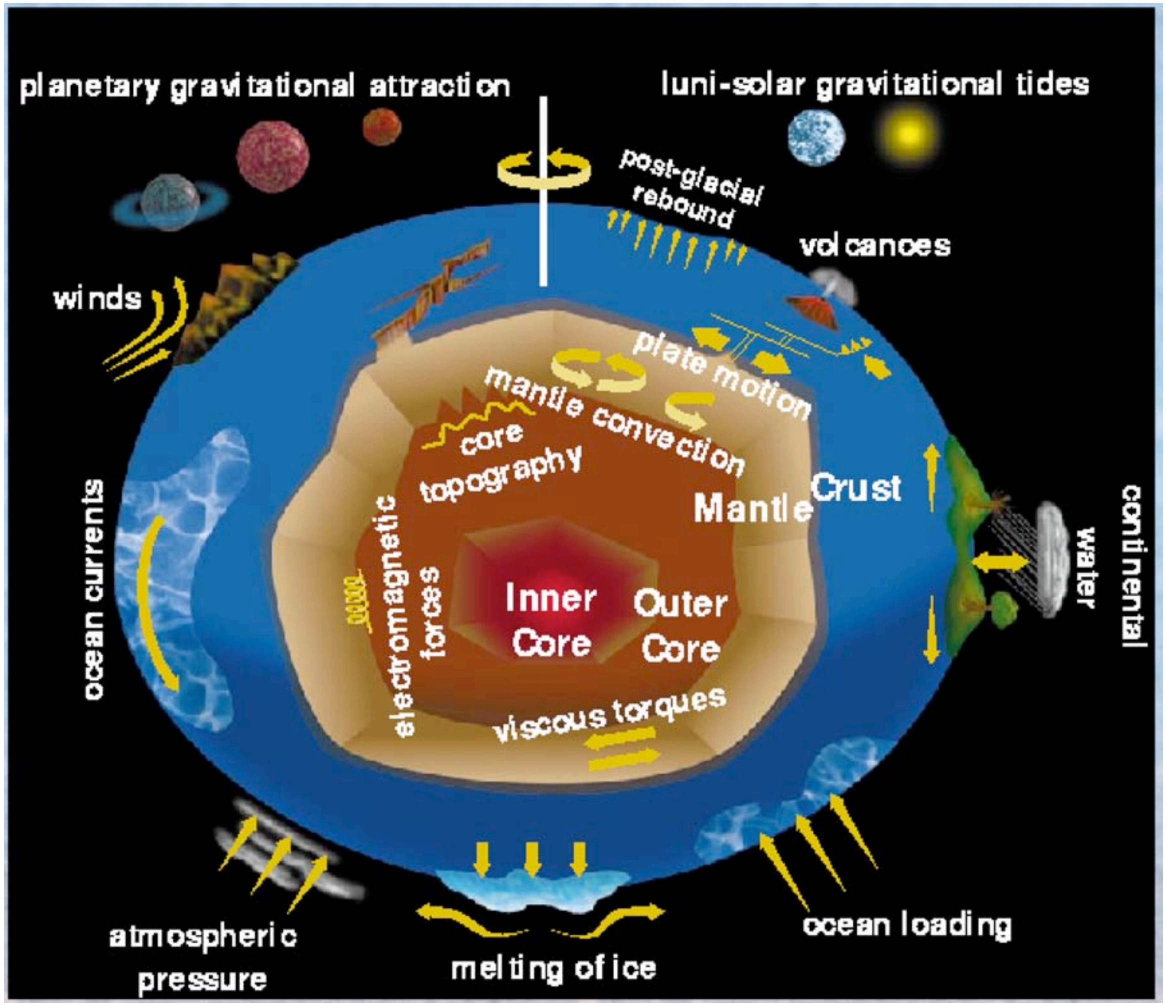
- SLR 2000	Jan/Tom	20 minutes
- VLBI	Chopo	20 minutes
- 48 " Telescope Facility	Jan	20 minutes

Space Geodesy

Why, How, Where

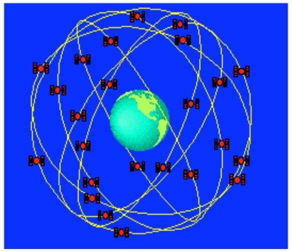
Chopo Ma, Code 698

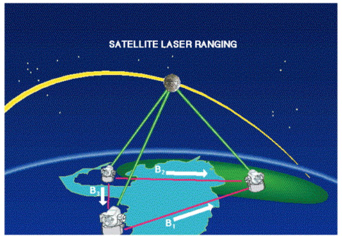
Causes for Crustal Motions and Variations in Earth Orientation

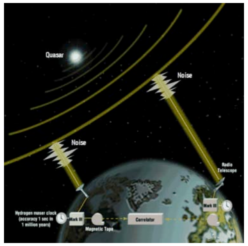


What are the geodetic networks?

- The Terrestrial Reference Frame (TRF) is an accurate, stable set of positions and velocities.
- The TRF provides the stable coordinate system that allows us to link measurements over space and time.
- The geodetic networks provide data for determination of the TRF as well as direct science observations.
- GPS, SLR, and VLBI are the three technologies used in the geodetic networks.





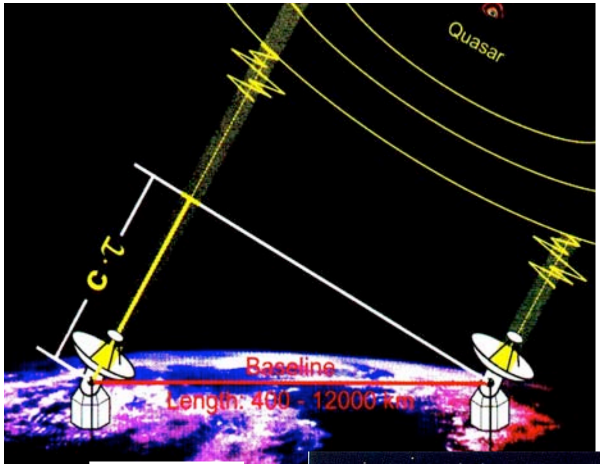


What do the geodetic networks do for NASA?

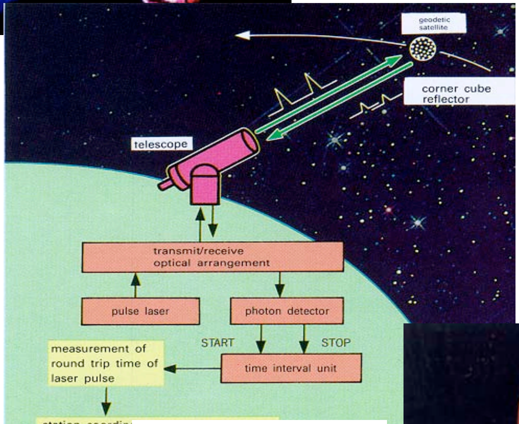
- **Directly measure Earth science parameters**
  - e. g., volcanic and tectonic deformations, gravity field, Earth rotation
- **Provide the accurate TRF for the interpretation of satellite observations**
  - e. g., altimetry
- **Precise determination of the orbits of satellites**
  - GRACE, TOPEX, Jason, LAGEOS, and many others
- **Provide critical information for accurate deep space navigation**

Space Geodesy Techniques

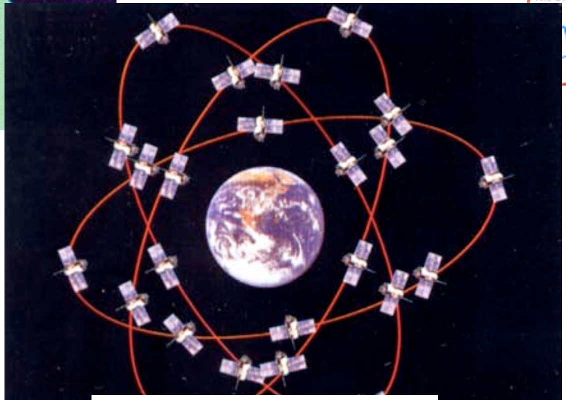
- VLBI **(Very Long Baseline Interferometry)**
- SLR/LLR **Satellite/Lunar Laser Ranging**
- GNSS **(GPS, GLONASS, future: Galileo)**
- DORIS **(Doppler Orbitography and Radio Positioning Integrated by Satellite)**



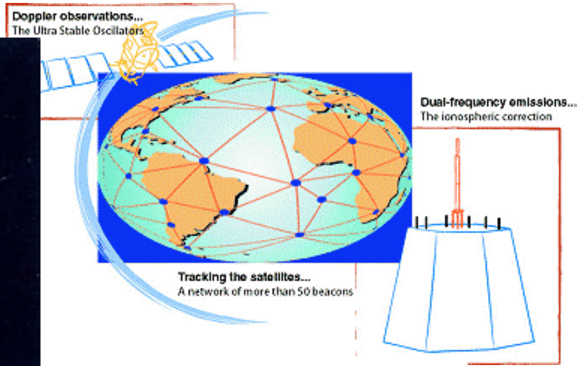
VLBI



SLR/LLR



GNSS/GPS



DORIS

SLR Unique Capabilities

The SLR Technique

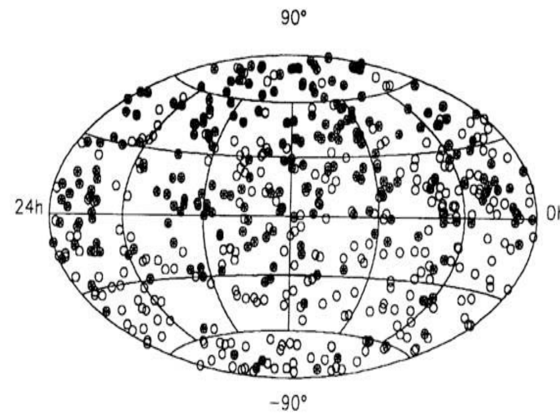
- Precise range measurements to satellites
- Least dependent on transmission media
- Passive space segment
- Near real-time global data availability
- Ability to detect variations in long-term trends

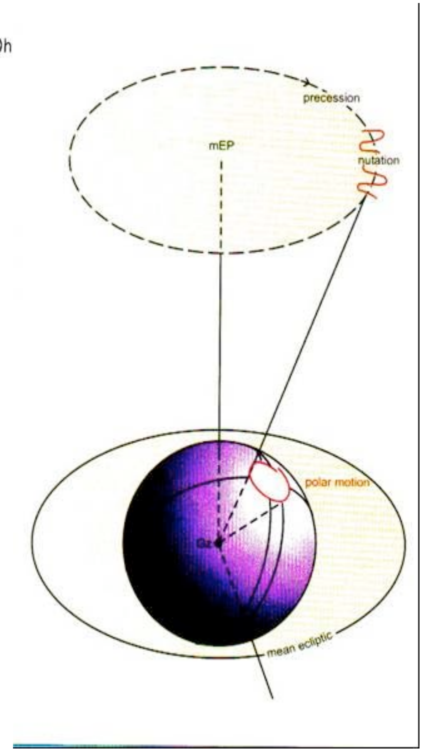
Science and Applications

- Terrestrial Reference Frame (Center of Mass and Scale)
- Static and time-varying coefficients of the Earth's gravity field
- Earth mass distribution
- Earth Orientation Parameters (EOP)
- Accurate satellite ephemerides: POD calibration and validation of altimetry missions
- Special Missions - Tether Dynamics, etc.
- Backup Precise Orbit Determination (POD)

VLBI Unique Capabilities

- Celestial Reference Frame using quasars
- Motion of axis in space
- Earth rotation rate
- Differential navigation for spacecraft





Why do we have three techniques?

- **High precision geodesy is very challenging**
  - Accuracy of 1 part per billion
- **Fundamentally different observations with unique capabilities**
- **Together provide cross validation and increased accuracy**

Technique **Signal** **Source** **Obs. Type**	**VLBI** **Microwave** **Quasars** **Time difference**	**SLR** **Optical** **Satellite** **Two-way range**	**GPS** **Microwave** **Satellites** **Carrier phase**
Celestial Frame **UT1**	Yes	**No**	**No**
Scale	Yes	Yes	**Yes**
Geocenter	**No**	Yes	**Yes**
Geographic Density	**No**	**No**	Yes
Real-time	**No**	**No**	Yes
Decadal Stability	Yes	Yes	**Yes**

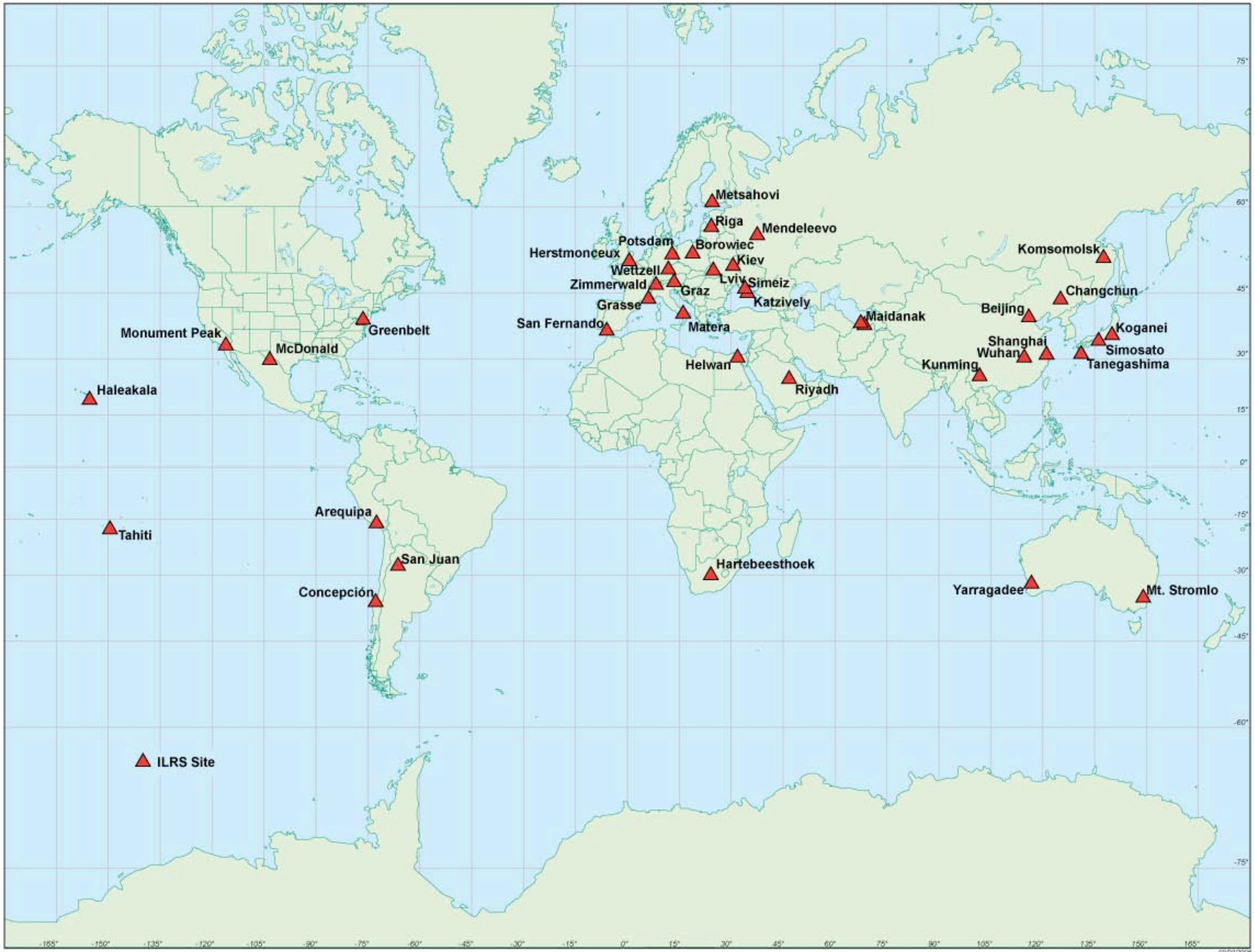
What are the products?

- TRF: 3-D station positions and temporal evolution
- Earth rotation
- Static and temporal variations in Earth's gravity field
- Time transfer
- Raw data for other science users
- Precise orbits
- Atmospheric and ionospheric parameters

Who are the users of the data?

- NASA and non-NASA Flight Missions
- NSF Polar Programs
- USGS National Earthquake Hazards Reduction Program
- DoD
- Land Surveyors
- NOAA/NGS
- …

SLR Site Map



Metsahovi
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Herstmonceux
Kiev
Wettzell
Lviv
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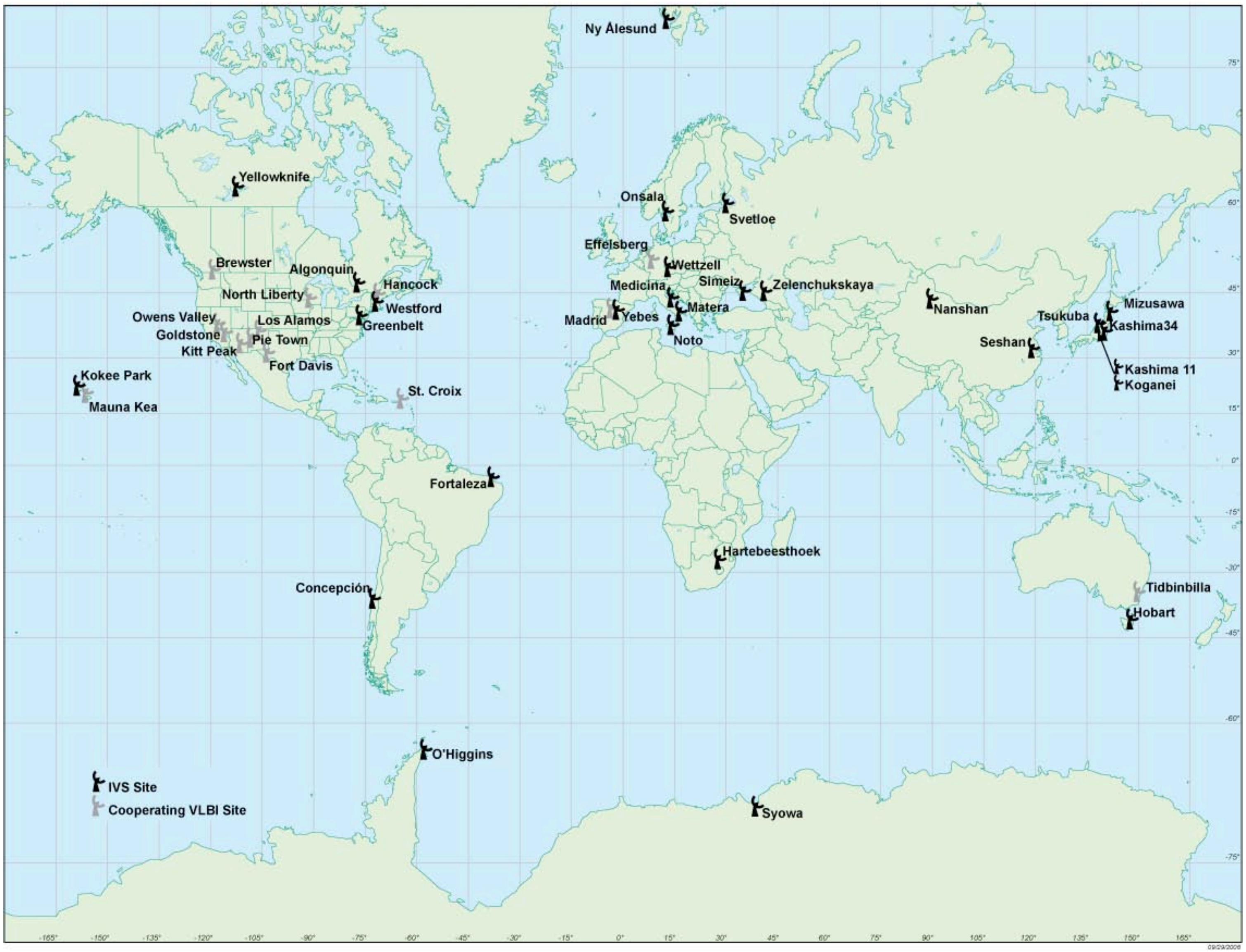
Zimmerwald
Graz
Katzively
Grasse
San Fernando
Matera
Maidanak
Komsomolsk
Changchun
Beijing
Koganei
Shanghai
Wuhan
Simosato
Tanegashima
Kunming
Helwan
Riyadh
Monument Peak
McDonald
Greenbelt
Haleakala
Arequipa
Tahiti
San Juan
Concepción
Hartebeesthoek
Yarragadee
Mt. Stromlo
ILRS Site

VLBI Site Map



GNSS Site Map

DORIS Site Map

What are the geodetic services?

- **Parts of the International Association of Geodesy (IAG)**
- **An example of Community Management Model**
  - Develop standards
  - Self regulating
  - Performance monitoring
  - Define and deliver products
- **200+ Organizations in 80+ countries**
- **NASA actively participates in the services**
  - International GNSS Service (IGS)
  - International Laser Ranging Service (ILRS)
  - International VLBI Service (IVS)
  - International DORIS Service (IDS)
- **Services respond to NASA's program needs**

NASA's role among global collaborators

- **Networks, through the TRF, provide critical infrastructure to support flight projects.**
  - This support is assumed by current and future missions to be provided *yet is rarely budgeted or planned*.

- **NASA leverages its resources by cooperating with international partners.**
  - NASA supports and coordinates the geodetic services through central offices at JPL (IGS) and GSFC (ILRS and IVS).
  - This NASA coordination is a highly successful international activity endorsed by international organizations such as the IAG.
  - NASA's space geodetic data sets are augmented by data contributed by other agencies to the international pool.
  - These activities are supported by the Crustal Dynamics Data Information System (CDDIS), a key data center supporting the IGS, ILRS, IVS, IDS, and IERS.
  - This results in access to greater and enhanced data sets and products.

NASA Needs for Geodetic Networks

- Long term, systematic measurements of the Earth system require the availability of a terrestrial reference frame (TRF) that is stable over decades and independent of the technology used to define it.

- The space geodetic networks provide the *critical infrastructure* necessary to develop and maintain the TRF and the needed terrestrial and space borne technology to support the Earth science goals and missions.

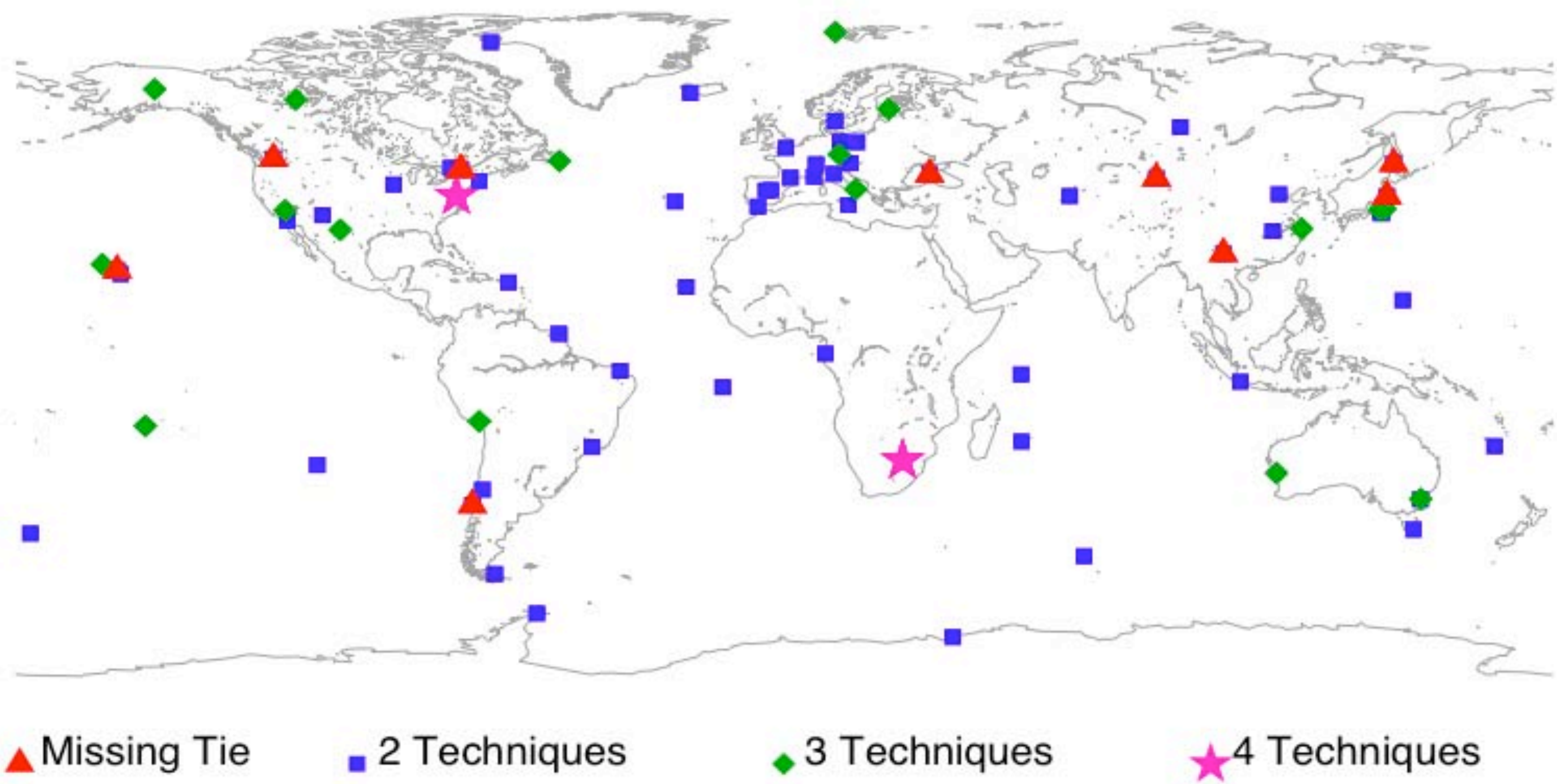
- This infrastructure is composed of the:
  - Physical networks,
  - Technologies that compose them, and
  - Scientific models and model development that define a TRF.

A TRF is a set of positions and a model for how those positions evolve with time

Co-location of Space Geodesy Techniques

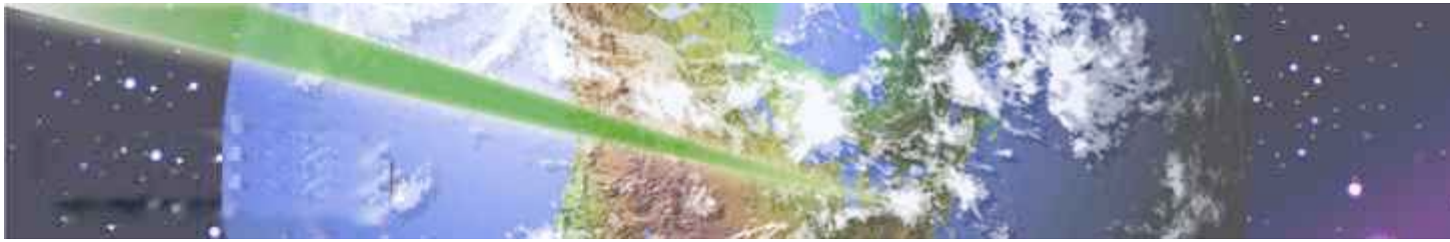
- **Importance of co-location**
  - Co-location ties techniques together, enables combination for TRF
  - Local ties
    - accurate measurements of vectors between reference points for different techniques at a site
    - essential for combination of data from different techniques
    - limiting factor in connecting the networks
- **Approach and strategy**
  - Improve local tie measurements.
  - Understand different solution results for each technique at a site.
  - Improve the co-location network.
  - Investigate new technology approaches to measuring local ties.

Distribution of Space Geodesy Co-Location Sites Since 1999



Space Geodesy Program Issues

- **Loss of organization structure**
  - Space Geodesy Networks Office and Geoscience Technology Office disbanded
- **Nonreplacement of management and technical staff**
  - J. Bosworth, T. Clark, J. Degnan, …
- **Expanded activities with flat or declining funding**
  - Formation of geodetic services with key components at GSFC
- **Single point of expertise**
  - Only one long-term civil servant for SLR networks and for VLBI group



Satellite Laser Ranging Program Overview

David Carter

Goddard Space Flight Center
Code 453
Greenbelt, Maryland

October 4, 2006

Map of International Laser Ranging Service (ILRS) Network

MOBLAS System at GSFC

NASA SLR System Characteristics

MOBLAS

MLRS

- Single person operations per shift
- Hourly data delivery with near real-time capability
- Sub-centimeter ranging precision
- 5 to 10 Hz Repetition Rate
- Aircraft Monitoring: Radar system/mount observer

TLRS

HOLLAS

Milestone Dates for SLR 2000 Prototype Development

- Nov. 1993: Dr. Dave Smith (920) asked Dr. John Degnan (920) to design a "low cost automated SLR 2000" system.
- Apr. 1997: Shapiro Report, SLR Review by NASA HQ. Recommendations presented to Bill Townsend (Assoc. Admin. For Code Y) and Bob Price (Director, Mission to Planet Earth (MTPE)).
- Aug. 1997: SLR 2000 Technology Review by MTPE.
- FY98: First dedicated funding released for SLR 2000 development ($1.2M).
- Jun. 2001: SLR 2000 Status Review by NASA HQ Code Y.
- Dec. 2003: SLR Budget Reduction Meeting, NASA HQ Code Y, presented to Mike Luther (Deputy Director Code Y). SLR program budget reduced 40%.
- FY 2004: Management of SLR Program transferred from Code 920 to Code 453. Technical leadership for SLR 2000 prototype remained in Code 920.
- Jul. 2004: SLR 2000 Status Review by NASA HQ.
- Dec. 2004: Request for Information (RFI) released for replication of SLR 2000 Prototype system.
- Dec. 2005: Meeting at NASA HQ to discuss laser ranging support of LRO.

Code 450 Near-Term Actions

- **Assign Project Manager to SLR 2000 Development**

- **Refine Milestone Schedule & Cost Estimate for SLR 2000 Prototype**
  - Reflective of what current budget supports
  - Transition plan from prototype to system ready for replication

- **Provide Regular Project Status Reports to NASA HQ**

- **Provide NASA HQ with LRO Laser Ranging Cost and Benefits Analysis**

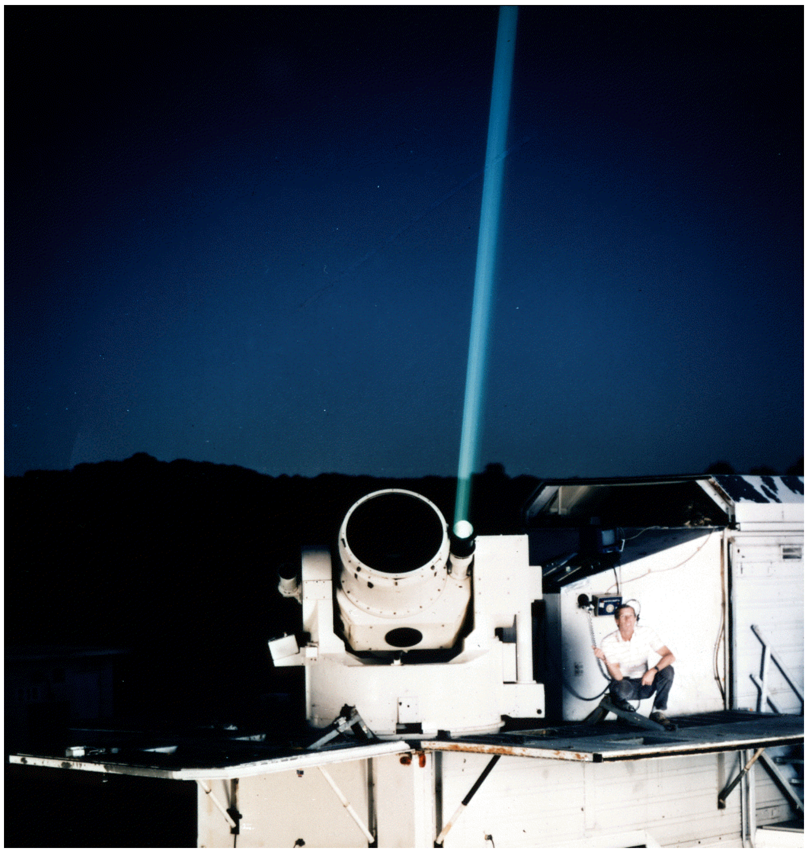
Next Generation Satellite Laser Ranging SLR2000

Tom Zagwodzki
Jan McGarry

NASA/GSFC

October 4, 2006

The Current NASA SLR Network



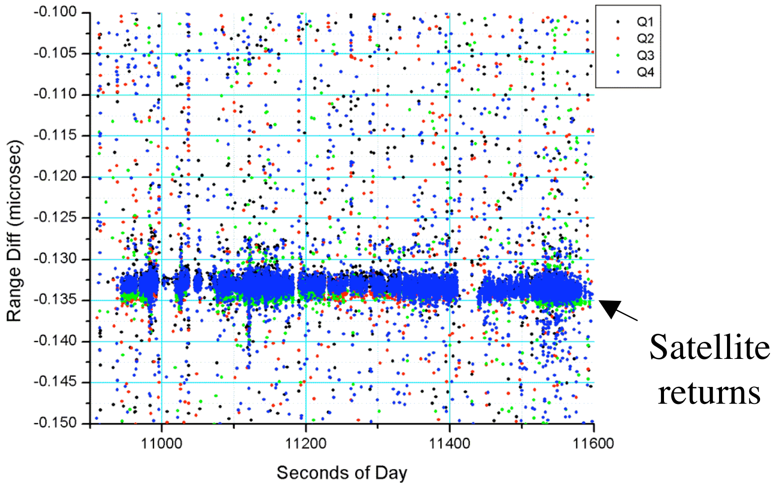
- Late 70’s technology
- Upgrade path exhausted after multiple subsystem upgrades
- Reduced to single man operation but still costly to operate/maintain
- Operator health/safety hazards still exist (chemical/electrical/ocular)
- Limited spare parts available
- More tracking demands
- Limited tracking capability for GPS (20,000 km) and beyond

New instrumentation, enabling technologies, and more computing power hint of the future...

SLR2000 Prototype Development at GGAO

The SLR2000 is a low energy/high repetition rate singe photon detection laser ranging system capable of tracking cube corner equipped satellites in earth orbit. The concept of SLR2000 was developed as the next generation NASA Satellite Laser Ranging system in Code 924. Technical development continues in code 694 with SLR OPS in code 453. The system is currently undergoing final prototype testing at the GGAO and has demonstrated tracking of low earth orbit satellites.

OMC ranging plot of satellite returns



System Characteristics

- 2 Khz, 532nm wavelength, 135 uJ/pulse, 300psec pulsewidth laser operation with single photon detection receiver
- Common path transmit/receive optics
- 40cm diameter off axis telescope
- 1 to 2 arcsec pointing/tracking accuracy
- Narrow (~10 arcsec) laser transmitter beamwidth and receiver FOV (Field of View)
- Independently steered laser point ahead

Next Generation SLR System Goals

Human operator can be replaced
- Smart weather instrumentation to access tracking conditions
- Automated console operations for system tracking and calibrations
- Automated closed loop satellite tracking algorithms
- Automated scheduling, flow and analysis of data products

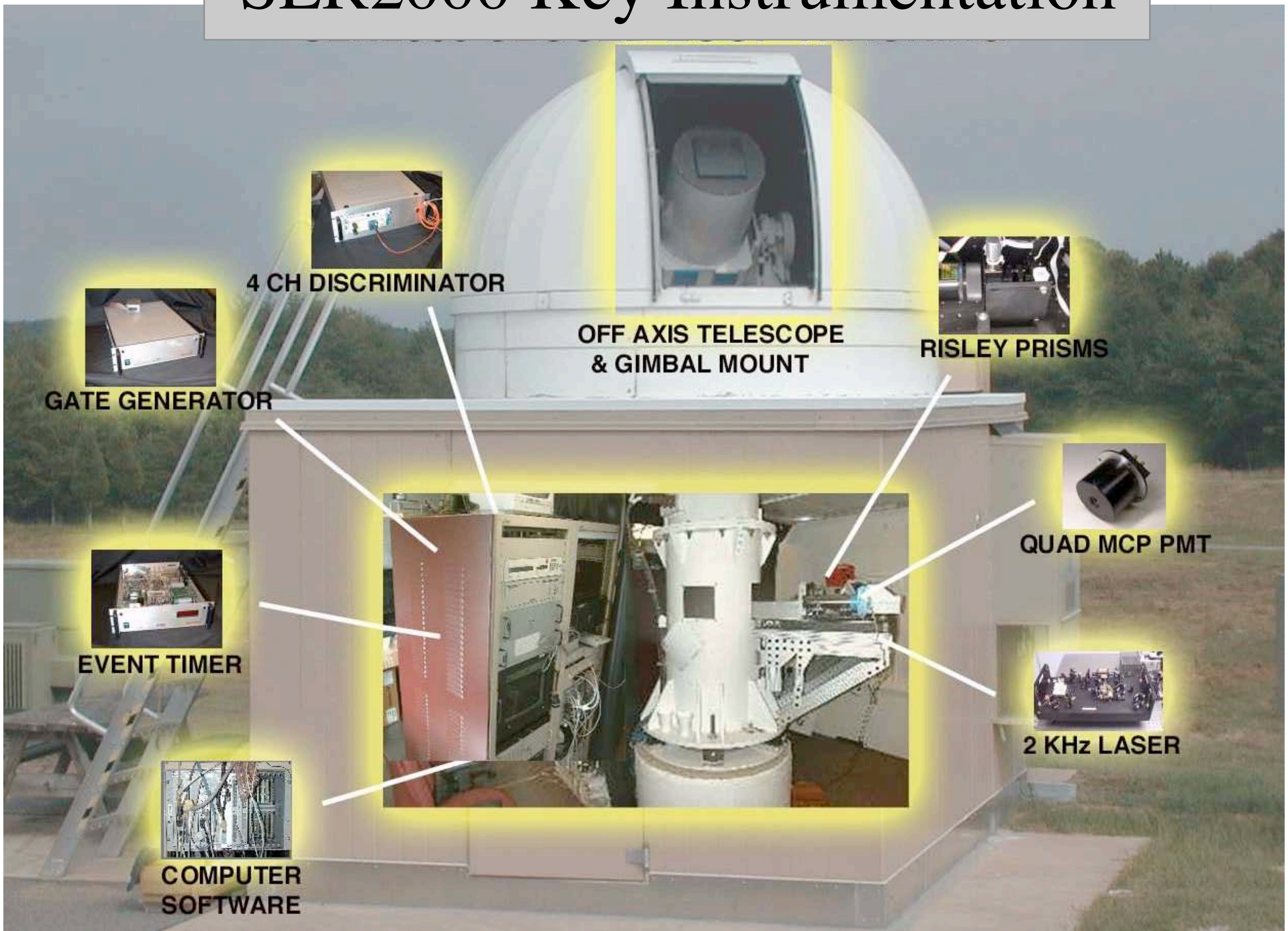
Health and safety issues have been addressed
- Electrical, chemical, and fume hazards have been retired
- Eyesafe laser tracking operations

Reduced system replication and operation costs
- Small, compact, low maintenance, increased reliability
- Automated internet data flow
- Central processing facility monitoring multiple stations

Innovative Hardware Developed for SLR2000

- **New quadrant microchannel plate photomultiplier tube (PMT)**
- **Passive 2 kHz Transmit/Receive switch**
- **Full aperture telescope use (eyesafe)**
- **Risley prism point ahead of transmit beam**
- **All sky thermal IR camera to assess cloud conditions**
- **2 kHz Event Timer/Range and Gate Generator**
- **Closed loop tracking with quadrant timing detector**
- **Signal recognition algorithms, 5 operational CPUs, more than 100K lines of code, and more than 20 M.Y. software effort**

SLR2000 Key Instrumentation



Challenges in completing the SLR2000

•Reliable closed loop quadrant tracking of LEOs and LAGEOS

•Photomultiplier tube lifetime issue is being addressed. To minimize exposure three levels of protection are being implemented: 1) PRF control to avoid "collisions" , 2) Optical LC shutter to minimize laser back scatter into the receiver, and 3) Hardware blanking to disable receiver range gating when the laser fires.

•Tracking of GNSS satellites (GPS, Galileo, GLONASS, etc). Very low signal level will require long frame lengths.

•Automation of tracking decisions based upon sky camera cloud cover.

SLR2000 Development Milestones - CY ‘06

•Installation/calibration/operation of new higher performance star camera for more accurate mount error modeling

•Installation/alignment/optimization of LC (liquid crystal) optical shutter in the Transmit/Receive switch to protect the photomultiplier tube

•Installation/check out of new high quantum efficiency (>30%) quadrant photomultiplier tube

•Closed loop daylight tracking of LEO satellites and night time LAGEOS

•Installation/calibration/check out of new thermal IR sky camera

•Laser fire rate control analysis for collision avoidance

•Match link analysis to actual tracking results and reevaluate laser transmit energy requirement

Future SLR2000 Tracking Support

LRO tracking in ’08 –’09

•Value added to NASA SLR:

- High energy 532nm laser (and spare) capable of tracking ALL earth satellites night or day as well as planetary and deep space transponder instruments (albeit 6 nsec pulsewidth)
- Laser safety RADAR dedicated to SLR2000
- An extra access port for future expansion (ie. Laser com or other SLR work)
- A funded 2 shift single man operator available for some SLR operations
- Additional funding for making SLR2000 operational, and a set of critical spares
- Demonstrated tracking capability which opens the door for future operations and optical tracking programs

The Goddard Geophysical and Astronomical Observatory

Jan McGarry (694)
Tom Zagwodzki (694)
Chopo Ma (698)
David Carter (453)
Mike Perry (HTSI)

October 4, 2006

Goddard Geophysical and Astronomical Observatory (GGAO) formerly Goddard Optical Research Facility (GORF)

Photo ~1980

- Located ~ 3 miles from GSFC on Springfield Road (in middle of BARC).

- 48” telescope, VLBI MV3, GPS, and numerous other facilities and experiments.

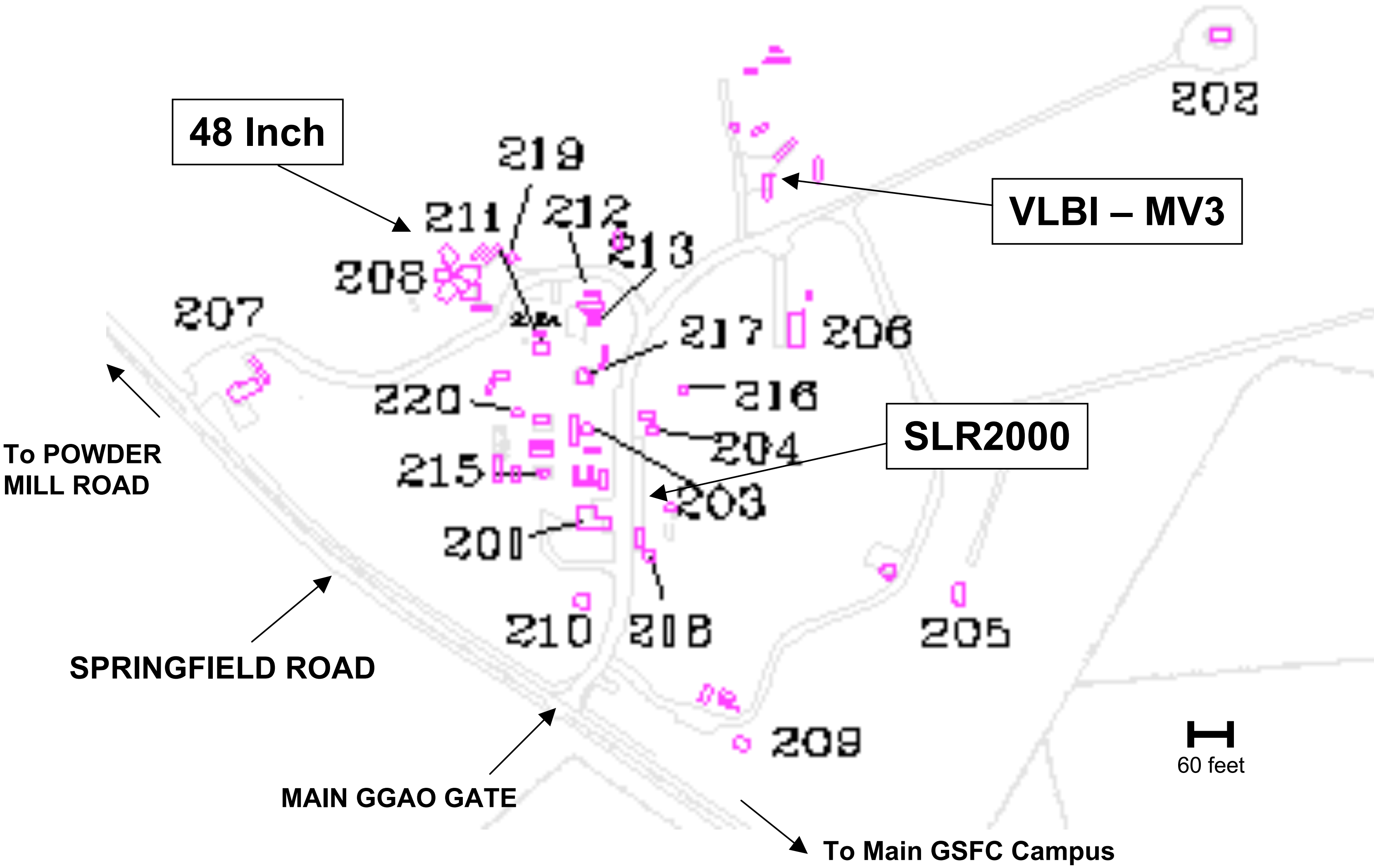
- GGAO has been the site of all NASA SLR system development, testing and collocations. The Italian MLRO system, Saudi SALRO, and other ILRS systems have also been developed and tested at site.

Facilities and Users

GGAO is one of only a few sites in world to have all 4 geodetic techniques collocated: SLR, VLBI, GPS, DORIS

- **Operational SLR – MOBLAS-7 (453): David Carter**
- **R&D SLR – SLR2000 (453/694): Carter / Zagwodzki / McGarry**
- **R&D SLR – 48” Telescope (694): Zagwodzki / McGarry**
- **VLBI – MV3 (698): Ma / Rubincam**
- **DORIS beacon and GPS Receiver (698): Ma / Rubincam**
- **Low Freq Interferometry (695): Bob MacDowall**
- **X-Ray beamline (662): Keith Gendreau**
- **36” Telescope: *unclaimed after code 600/900 reorganization***
- **Clubs:**
    - **Explorer Scout Post – John Wolfgang**
    - **Astronomy Club - Kevin Hartnett**

MAP OF GGAO



48 Inch
VLBI – MV3
SLR2000
202
219
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220
216
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203
201
210
218
205
209
To POWDER MILL ROAD
SPRINGFIELD ROAD
MAIN GGAO GATE
To Main GSFC Campus
60 feet

VLBI at GGAO (MV3)

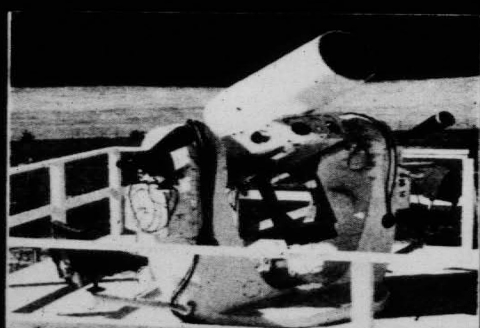
- Antenna originally mounted on a trailer as a mobile VLBI system
- Test bed for e-VLBI (transmission of data by network)
- Planned test bed for NASA development of next generation VLBI system

MV3 antenna:
5m vs typical 20m
geodetic antenna

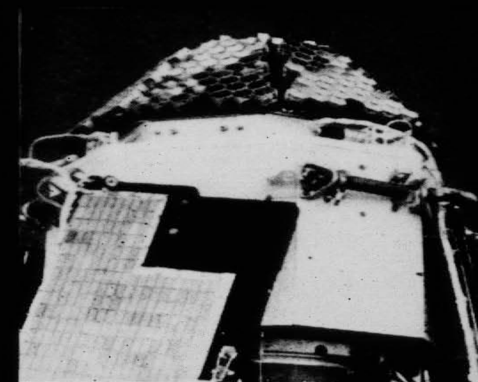
Primary GPS

SLR BEGINS: GSFC records first SLR returns ever on Oct 31, 1964 (GSFC team lead by Henry Plotkin)

SATELLITE LASER RANGING - 1964



TRANSMITTING LASER AND RECEIVING TELESCOPE, MOUNTED ON A MODIFIED NIKE-AJAX RADAR PEDESTAL.



THE BEACON EXPLORER-B SATELLITE WITH ARRAY OF CUBE-CORNER REFLECTORS.

GODLAS

BE-B: first satellite with retro-reflectors

Satellite Laser Ranging was first developed at GSFC

GGAO SLR: PAST, PRESENT and FUTURE

PAST: GODLAS

PRESENT: MOBLAS-7

FUTURE: SLR2000

Continuous set of GGAO SLR data since 1964

48 Inch (1.2 Meter) Telescope Facility at GGAO

Multi-user facility built in 1973-74.
Arc-second precision tracking telescope.

48” Telescope is an R&D Facility used in many experiments:

- Field testing of bread board for optical heterodyne spectrometers in 1970s & 1980s (M. Mumma & colleagues).
- Automated guiding and two-color refractometry (D. Currie & D. Wellnitz / UMd): 1970s.
- Lunar laser ranging test facility (C. Alley / UMd): 1980s.
- Comparison of one way propagation times of laser pulses (East-West vs West-East) by C. Alley and R. Nelson in 1983.
- Single and two-color satellite laser ranging test bed (Zagwodzki, Degnan, McGarry): 1980s & 1990s.

- Mercury Laser Altimeter (MLA) Earthlink 2-Way Laser Ranging. MLA onboard MESSENGER at distance of 24 Mkm (Smith, Zuber, Sun, Neumann, Zagwodzki, McGarry): May 2005.
- Mars Orbiter Laser Altimeter (MOLA) Earthlink 1-Way Laser Ranging. MOLA onboard MGS orbiting Mars at ~80 Mkm (Smith, Zuber, Abshire, Sun, Neumann, Zagwodzki, McGarry): Sep 2005.

and many others…

GGAO ISSUES and CONCERNS

- **FUNDING**
  - Used to pay for alternate FOM and small amount of procurement: site cell phone, LAN repairs, misc site equipment repairs.
  - Costs are divided amongst active projects at site. Some can't afford to pay. Collecting enough money is hard.
  - Some facilities (eg 36" telescope and B205) have no funding and no support.
  - 48" telescope has had no serious funding for a decade. Encoders need replacement, mirrors needs recoating. Lasercom is expected to support some needed repairs.

- **CENTER INFRA-STRUCTURE SUPPORT**
  - Slow erosion of what center will cover (and has money for).
  - No center support for roll-back roofs (aka domes).
  - Many building at GGAO are in serious need of repairs that no one has money to perform.
  - Lawn care has been cut back severely in past few years. At some point this will become a health & safety issue (ticks & fire hazard).

Next Steps

- Develop and communicate to HQ:
  - Refined cost and schedule for transition of SLR2000 prototype to readiness for replication
  - Cost/Benefit of LRO support
- Develop with HQ an integrated plan for the future of space geodesy
  - SLR 2000
  - VLBI Path Forward
- Develop overall wellness program for GGAO